4. TRANSPORT AND PERSISTENCE

Factor 2 of the 10 factors used to determine no unreasonable degradation requires the assessment of the transport and fate of the discharged material through physical, chemical, and biological processes. This chapter describes these processes and the modeling used to assess their potential water quality and human health impacts (Chapter 9).

The discussion of transport processes affecting drilling wastes treats the two major waste streams, water-based drilling fluids (WBF) and synthetic-base drilling fluids (SBF) separately, due to differences in characteristics, mode of entry and behavior in the environment. The synthetic-based fluids associated with cuttings discharges are expected to behave differently from WBFs due to several important differences:

- Only SBF-cuttings are discharged, with retention of the SBF base fluid generally ranging between a low of 2 percent for the larger cuttings and a high of 20 percent for the smallest cuttings (fines). Effluent guidlines will limit the maximum retention to 6.9 percent. With WBFs, in addition to the WBF-cuttings, large volumes of WBF are discharged. Thus, for an equal volume of hole drilled, the volume of WBF-related discharge is expected to be much greater than the volume of SBF-related discharge.

- WBFs contain very high levels of suspended and settleable solids (and are, in fact, referred to as "muds" in the industry) that disperse in the water column and produce a plume with many fine particles that settle rather slowly. Hence, they may be transported large distances. SBF-cuttings, however, tend not to disperse in the water column nearly to the same extent as WBFs because the particles are "oil" wet with the synthetic material. Compared to WBF-cuttings, SBF-cuttings tend to be larger than WBF-cuttings. Again the reason is that SBFs do not disperse the cuttings particles to the same extent as WBFs. Because larger particles settle faster than smaller particles, SBF-cuttings tend to be deposited in a smaller impact area than WBF-cuttings.

- SBF-cuttings have a significant organic component that is not present in WBFs, namely the synthetic base fluid. The synthetic base fluid, in general, is insoluble in water and deposits in the sediment with the cuttings. The fluids seperation technologies used on SBF cuttings remove the fine cuttings, causing what remains to settle rapidly upon discharge and accumulate nearer the point of discharge than WBF wastes.

These differences suggest that discharge plumes characteristic of WBF discharges will not be an important mechanism for the transport of SBF wastes.

4.1 Water-Based Drilling Fluids

Drilling fluids contain quantities of coarse material, fine material, dissolved solids, and free liquids. While all of these components are affected by the momentum of the discharge jet, density-driven turbulent mixing, and diffusive processes, the larger particulates of drilling fluids separate more rapidly from the fines and soluble portions of the discharge plume due to the additional effect of gravitational

settling. Fall velocities are largely controlled by particulate size, with larger particulate separating out more rapidly from the plume. Upon discharge, this mixture appears to separate rapidly. An upper plume is formed from shear forces and local turbulent flow at the discharge pipe. This upper plume contains about five to seven percent, by weight, of the total drilling fluid discharge (Ayers et al., 1980b). This plume migrates to its level of neutral buoyancy while particulates slowly settle to the bottom and is advected with prevailing currents. The fine solids settle at a rate depending on aggregate particle size, which is very dependent on flocculation.

A lower plume contains the remainder of the discharged drilling fluids. Coarser materials fall rapidly out of the lower plume. Ayers et al. (1980b) found that the lower plume components deposited on the bottom within a few meters of the discharge point from an outfall located 3 meters below the surface in a water depth of 23 meters. In deeper waters, settleable solids will deposit over a larger area, depending upon the total fall depth, the settling velocity of the particles, and current speeds. If water depths are great enough to prevent bottom impact of the discharge plume, fine particulates in the lower plume will reach a level of neutral buoyancy and will be advected with ambient current flow, similar to their behavior in the upper plume.

Both upper and lower plumes are affected by three different transport processes or pathways: physical, chemical, and biological. Physical transport processes affect concentrations of discharge components in the water column through dilution[1], dispersion[1], and settling. Physical processes include currents, turbulent mixing, settling, and diffusion. These processes include current speed and direction, tidal regime, kinetic energy availability, and the characteristics of the receiving water such as water depth and density stratification. Physical processes are the most understood of the three transport pathways.

Chemical and biological processes more frequently produce changes in the structure and/or speciation of materials that affect their bioavailability and toxicity. Chemical processes include the dissolution of substances in seawater, particle flocculation, complexing of compounds that may remove them from the water column, redox/ionic changes, and absorption of dissolved pollutants on solids. Biological processes include bioaccumulation and biomagnification in soft or hard tissues, fecal agglomeration and settling of materials, and physical reworking to mix solids into the sediment (bioturbation).

4.1.1 *Physical Transport Processes*

Pollutant concentrations resulting from offshore platform discharges are influenced by several factors related to the discharge and the medium into which it is released. Discharge-related factors include the solids content of the effluent, distribution of particle sizes and their settling rates, effluent chemical composition, discharge rates and duration, and density.

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[1] In analyzing the impacts of discharged drilling fluids, the behavior of either the mud solids or the aqueous portion of the effluent can be measured. In this document, the term "dispersion" refers to tracking the behavior of the plume with respect to its solids content; dilution refers to a volumetric tracking of plume behavior and is intended to apply to soluble components of drilling fluids. The term "dispersion" in the ODCE does not necessarily refer to settling and removal of solids from the water column as they settle on the seafloor, but may also only refer to the concentration of suspended solids in the water column.

Environmental factors that affect dispersion and transport of discharged materials include current speed, current direction, tidal influences, wave action, wind regime, density structure of the water column, topography of the ocean bottom, bottom currents, and turbulence caused by platform wake. These factors influence dispersion and dilution of effluents in the water column, and resuspension and transport of solids settled on the seafloor. Areas of high hydrodynamic energy will disperse discharges more rapidly than less energetic areas. Current speed and boundary conditions also affect mixing because turbulence increases with current speed and proximity to the seafloor. Currents and turbulence can vary markedly with location and site characteristics and affect the movement of suspended matter and the entrainment, resuspension, and advection of sedimented matter.

Two studies by Houghton et al. (1980; 1981) suggest that turbulence induced by submerged portions of the drilling platform also may significantly contribute to the dispersion of the muds. Houghton et al. (1981) concluded that turbulence became a major source of dispersion when current speeds ranged from 5 to 10 cm/sec (0.16 to 0.32 ft/sec) or greater. However, this wake-effect has not been systematically studied at other locations. Ray and Meek (1980), for example, observed little change in plume dilution at Tanner Bank, offshore southern California, with current speed variations between 2 and 45 cm/sec (0.076 and 1.48 ft/sec).

Physical Transport Processes Affecting the Upper Plume

The upper plume contains only a small portion of the discharge effluent (some 5%), which is split off from the main, lower plume and is thought to be due to sheer forces in the immediate vicinity of the discharge pipe. Finer suspended materials are contained in the upper plume. Relative to the lower plume, the initial mixing of the upper plume (in which the momentum of the initial jet is dissipated) is less of a factor, and passive diffusion (in which the plume is transported at the speed and direction of prevailing currents) is a more important factor Sinking rates of solids in the upper plume will largely depend on the following four factors:

- Discharged material properties
- Characteristics of receiving waters
- Currents and turbulence
- Flocculation and agglomeration.

The physical properties of the discharged materials affect mixing and sedimentation. For suspended clay particulates, particle size and both physical and biological flocculation will determine settling rates. While oil exhibits little tendency to sink, it has displayed the ability to flocculate clay particles and to adsorb to particulates and sink with them to the bottom (Middleditch, 1980).

One of the major receiving water characteristics influencing plume behavior is density structure and stratification. In a stratified water column, density drives the collapse of the plume, i.e., the spreading of the plume at its level of neutral bouyancy. After sufficient spreading, the spreading rate of the plume from dynamic forces declines to a rate comparable to that resulting from turbulence ("far-field" or "passive" dispersion). Density stratification may concentrate certain components along the pycnocline. If flocculation produces particles large enough to overcome the barrier, settling will continue. If density stratification is weak or the pycnocline is above the discharge point, it may not affect plume behavior.

Ecomar (1978), as reported in Houghton et al. (1981), noted that upper plumes in the Gulf of Mexico follow major pycnoclines in the receiving water. A similar finding has been observed by Trefry et al. (1981), who traced barium levels along pycnoclines. This type of transport is a potential concern because sensitive life stages of planktonic, nektonic, and benthic organisms may collect along the pycnocline. Ayers et al. (1980a) observed that the bottom of the upper plume followed a major pycnocline after drilling fluid discharges at rates of 275 bbl/hr and 1,000 bbl/hr in the Gulf of Mexico.

Flocculation and agglomeration affect plume behavior by increasing sedimentation rates as larger particles are formed. Flocculation is enhanced in salt or brackish waters due to increased cohesion of clay particles (Meade, 1972). Agglomeration also occurs when larger particles are formed from a number of smaller ones through the excretion of fecal pellets by filter-feeding organisms.

Most studies of upper plume behavior have measured particulate components and paid less attention to the liquid and dissolved materials present. Presumably, these latter components are subject to the same physical transport processes as particulate matter, with the exclusion of settling. Studies suggest that suspended solids in the upper plume may undergo a higher dispersion rate than dissolved components.

Houghton et al. (1980) measured upper plume transport in Lower Cook Inlet, using a soluble, fluorescent dye (fluorescein) in current speeds of 41 to 103 cm/sec. The water depth at the site is 63 m (207 ft) but the plume never sank below 23 m (75 ft). From transmissometry data collected in the Gulf of Mexico, Ayers et al. (1980b) estimated upper plume volume and found that a 275 bbl/hr drilling fluid discharge exhibited a dilution ratio of 32,000:1 after 60 minutes and a 1,000 bbl/hr discharge showed a dilution ratio of 14,500:1 after 62 minutes. Dispersion ratios for suspended solids at these distances would be approximately one to two orders of magnitude greater than for soluble components.

From radiotracer data collected for offshore Southern California and Cook Inlet, Petrazzuolo (1983) estimates dilution rates of "soluble" tracers (based on generalized estimates of distances to specified levels of dispersion; Table 4-1).

Physical Transport Processes Affecting the Lower Plume

The physical transport processes affecting the lower plume differ little in nature from those influencing the upper plume; differences are more related to the relative contribution of the various processes. The lower plume contains the main body of the discharged material. The initial momentum of the discharge jet is more dominant a factor in lower plume behavior, but is still followed by a dynamic collapse phase and then passive diffusion. The lower plume contains a component composed of coarser material that settles rapidly to the bottom regardless of current velocity. This rapid settling is most pronounced during high-rate bulk discharges in shallow waters. With the high downward momentum of these discharges, the plume reaches the bottom. At Tanner Bank, the lower plume was relatively unaffected by average currents of 21 cm/sec (0.69 ft/sec) and bottom surges of up to 36 cm/sec (1.18 ft/sec; Ecomar, 1978).

Table 4-1. Estimates of Distances Required to Achieve Specified Levels of Dilution of a Soluble Drilling Fluid Tracer in the Upper Plume at Fixed Current Speeds based on Field Study Data[a]

Dilution Criterion	Distance Required (m)[b]		
	Current Speed (cm/sec)		
	5	10	15
10^4	10 - 17	19 - 34	29 - 51
10^5	80 -146	169 - 291	240 - 437
5×10^5	355 - 657	709 - 1,313	1,063 - 1,970
10^6	673 - 1,256	1,345 - 2,512	2,018 - 3,768

[a]   Source: Petrazzuolo, 1983.
[b]   Ranges in distances represent discharge rates of 21 to 1,200 bbl/hr.

The amount of fine solids settling to the bottom from the lower plume appears to depend to some degree on the aggregation of clay particles, which in turn depends on suspended material concentration, salinity, and the cohesive quality of the material. Fine particles tend to flocculate more readily than larger particles. Houghton et al. (1981) cites earlier work by Drake (1976), which concluded that physical-chemical flocculation can increase settling rates an order of magnitude over rates for individual fine particles.

4.1.2 *Seafloor Sedimentation*

Houghton et al. (1981) produced an idealized pattern for drilling fluids sedimentation around an offshore platform located in a tidal regime (Figure 4-1). Zero net current was assumed. The area of impact may have been overestimated from the true field case. Because no initial downward motion was assumed, longer settling times and greater plume dispersion were achieved. The result was an elliptical pattern, with the coarse fraction (10 mm-2 mm) deposited within 125 to 175 m of the discharge point, the intermediate fraction (250 μm-2 mm) deposited at 1,000 to 1,400 m, and the medium fraction (250 μm-74 μm) deposited beyond that distance. This is the greatest areal extent of bottom sedimentation for continuous discharges under the assumed conditions. Discontinuous discharges will be transported by currents at the time of release, and will form a starburst pattern over time (Zingula, 1975).

Studies have shown the extent of drilling fluid accumulation on the bottom to be inversely related to the energy dynamics of the receiving water. Vertical mixing also appears to be directly related to energy dynamics. Analysis of sediments at Tanner Bank showed no visible evidence of cuttings or mud accumulation 10 days after the last discharge, even though over 800,000 kg (882 short tons) of solids had been discharged over an 85-day period (Ray and Meek, 1980). Size analysis also indicated little change in the grain size distribution.

Low-energy environments, however, are not subject to (or only intermittently subject to) currents removing deposited material from the bottom or mixing it into sediments. In the low-energy Mid-Atlantic environment, for example, Menzie (1982) reported that cuttings piles were visibly distinct one
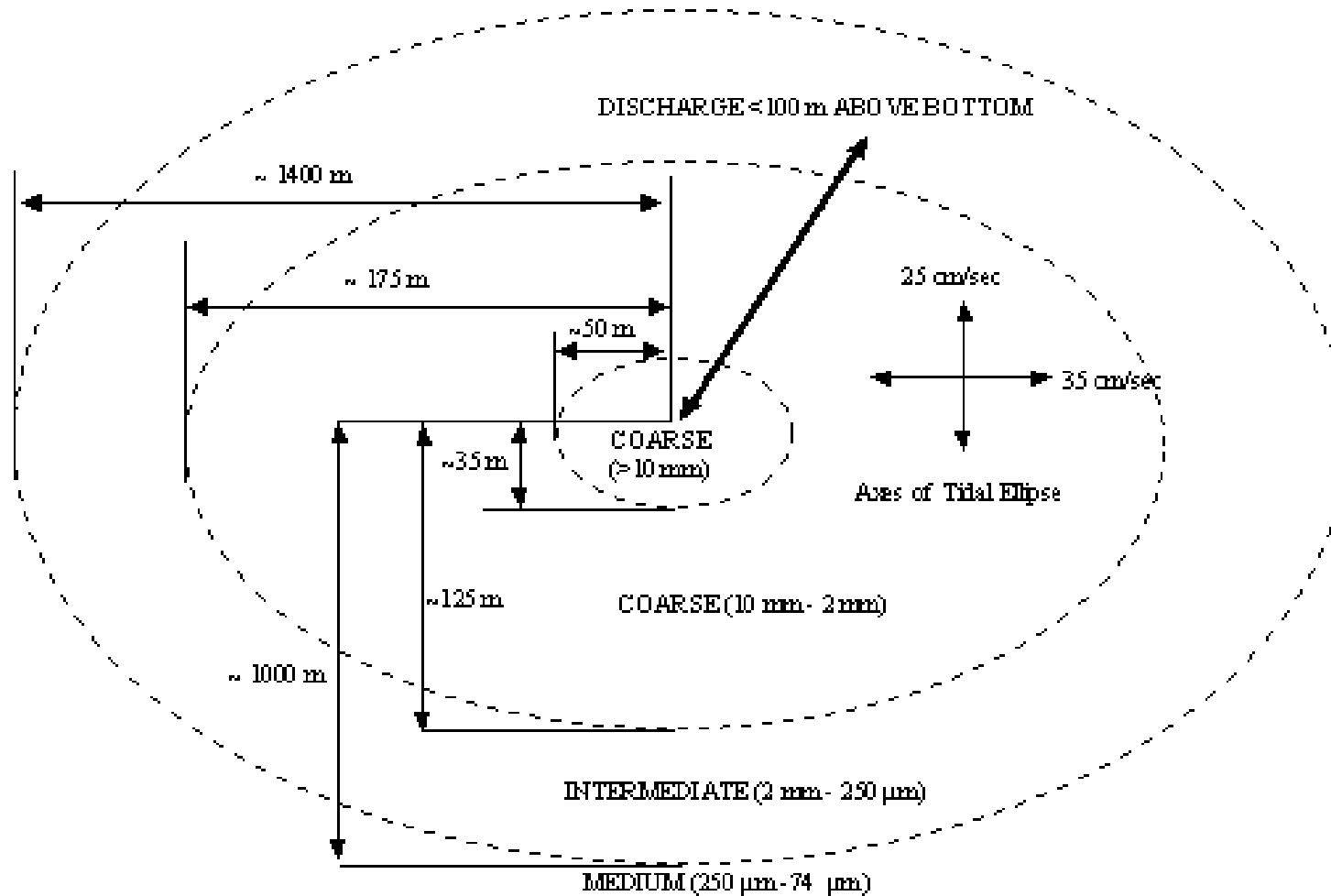
Figure 4-1. Approximate Pattern of Initial Particle Deposition (modified from Houghton et al., 1981)

year after drilling had ceased. Zingula (1975) also reported visible cuttings pile characteristics in the Gulf of Mexico shortly after drilling had terminated.

One study in the Gulf of Mexico (Ayers et al., 1980b) examined the short-term sedimentation of drilling fluids and cuttings in 23 m of water. Sediment traps were deployed only to a distance of 200 m. No distance-dependent quantitative estimates were possible from the data. More material, 10 to 100 fold, was collected in traps after a 1,000 bbl/hr discharge than after a 275 bbl/hr discharge. The relative barium, chromium, and aluminum contents of collected matter was more similar to that found in the initially discharged fluid for the 1,000 bbl/hr discharge than for the 275 bbl/hr discharge. This suggests a reduced influence of differential dispersion of drilling fluid components during the higher rate discharge.

Vertical incorporation of plume components into sediments is caused by physical and biological reworking of sediments. The relative contributions of these processes to vertical entrainment has not been well-described. Petrazzuolo (1983) cites a Gulf of Mexico operation where barium concentration was substantially enriched to a 4-cm (1.6 in) depth at both 100-m (330 ft) and 500-m (1,600 ft) distances. The upper 2 cm (0.8 in) of sediment was highly enriched with barium. This study was conducted along one transect (not aligned with major current flows) after four wells had been drilled at the platform. Boothe and Presley (1985) describe excess sediment barium concentrations that penetrate to depths of 5 to 20 cm (up to 30 cm at 30 m from one well site), with penetration depth generally decreasing with distance from the well site.

4.1.3 *Biological Transport*

Biological transport referes to the movement of pollutants through the environment via biological processes. Bioaccumulation, the accumulation of tissue burdens of pollutants contributes to transport of pollutants through the food web through predation. Bioaccumulation is discussed in Chapter 5. Another pathway of biological removal of pollutants involves a process known as bioturbation, benthic organisms reworking sediment and mixing surface material into deeper sediment layers.

Bioturbation generally mixes surface components into deeper sediment layers, although bioturbation can also expose previously buried materials. No work was found to quantify bioturbation effects, although a few studies have observed organisms living on a cuttings pile or in the vicinity of drilling discharges (Menzie et al., 1980; Ayers et al., 1980b). However, if the environment is one which rapidly removes cuttings piles, or where physical forces dominate resuspension and reworking processes, then biological mixing activities may not prove significant.

4.1.4 *Chemical Transport Processes*

Chemical transport of drilling fluids is poorly described. Much must be gleaned from general principles and studies of other related materials. Several broad findings are suggested, but the data for a quantitative assessment of their importance are lacking. Chemical transport will most likely arise from oxidation/reduction and reactions that occur in sediments. Changes in redox potentials will affect the speciation and physical distribution (i.e., sorption-desorption reactions) of drilling mud constituents.

Dissolved metals tend to form insoluble complexes through adsorption on fine-grained suspended solids and organic matter, both of which are efficient scavengers of trace metals and other contaminants. Trace metals, when adsorbed to clay particles and settled to the bottom, are subjected to different chemical conditions and processes than when suspended in the water column. If the sediments become anoxic, conversion of metals to insoluble sulfides is the most probable reaction, and the metals are then removed from the water column. Environments that experience episodic sediment resuspension favor metal release if reducing conditions existed previously in buried sediments; such current conditions also allow further exposure of organic matter complexes for further reduction and eventual release.

Alterations in Sediment Barium Levels

The long-term fate of discharge drilling fluids has been followed in several studies using sediment barium levels as a tracer. Four studies have been performed in the Gulf of Mexico from which data have been analyzed to estimate the dispersion of sediment barium. The subsequent fate of deposited material depends primarily on the physical processes that resuspend and transport particulates or entrain them into the sediments. Biological or chemical factors also could be important in stabilizing or mobilizing the material on the seafloor (e.g., through covalent binding of sediments or bioturbation). High concentrations of barium persistently found near a well site suggest a lower energy bottom environment, which favors deposition. If elevated levels cannot be found, even soon after drilling, resuspension and sediment transport have taken place and a higher energy bottom environment is suggested.

A series of power-law regression analyses were developed to relate average barium levels to distances from the discharge source (Petrazzuolo, 1983). These equations predicted the distance-dependent decreases in sediment barium levels that were obtained in four field studies. A multivariate analysis was used to estimate average sediment barium levels with respect to distance and number of wells. At locations of approximately 100 m to 30,000 m from a nine-well platform, this analysis suggested that sediment barium data collected early in the development phase of an operation may provide accurate predictions of sediment barium levels later in the operation.

Data from exploratory drilling operations have been used to examine deposition of metals resulting from drilling operations. These data indicate that any of several metals may be deposited, in a distance-dependent manner, around platforms, including cadmium, chromium, lead, mercury, nickel, vanadium, and zinc. These sediment metal studies, when considered as a group, suggested that the enrichment of certain metals in surficial sediments may occur as a result of drilling activities (Table 4-2). While confounding factors occur in most of these studies (i.e., seasonal variability and other natural and anthropogenic sources of metal enrichment), discharged drilling fluids and cuttings are probably not the only drilling-related source. The only two metals clearly associated with drilling fluids that appear to be elevated around rigs or platforms are barium and chromium.

Metals that appear to be elevated as a result of drilling activities, and are not solely related to drilling fluids, include cadmium, mercury, nickel, lead, vanadium, and zinc. Cadmium, lead, and zinc in drilling fluids are the result of the use of pipe dope or pipe thread compounds. Mercury, nickel, and zinc may originate from sacrificial anodes. Cadmium, lead, and vanadium may also originate from the release of oil in drilling operations. This release can result from burning, incidental discharges or spills from the rig or supply boat traffic, or use of oil as a lubricant in drilling fluids. Vanadium also may derive from

wearing of drill bits. In a Gulf of Mexico platform study, brine (formation water) discharges were identified as an additional potential source of metal contamination.

Although a variety of trace metals were variously found to be enriched in the sediment, enrichment factors were generally low to moderate, seldom exceeding a factor of 10. The spatial extent of this sediment enrichment also was limited. Either of two cases occurred: enrichment was generally distributed but undetectable beyond 300-500 m, or enrichment was directionally based by bottom current flows and extended further (to about 1,800 m) within a smaller angular component. These considerations suggest that exploratory activities will not result in environmentally significant levels of trace metal contamination. A study in the Canadian Arctic found that mercury would be the best trace metal tracer of discharged fluids (Crippen et al., 1980). However, reanalysis of the data also has suggested that the alterations in sediment mercury levels may have resulted from construction of the gravel island.

Alterations in sediment trace metal levels resulting from development drilling operations have not been as well characterized as those from exploratory operations. Two efforts have been made to estimate spatial distribution and fate of discharged material from a two-well operation in the Gulf of Mexico. One industry-sponsored analysis indicates that 49 percent of discharged barium is dispersed beyond a radius of 1,250 m from the platform (Mobil Oil Corporation, 1978). Another analysis of these data indicates that 78 percent of the barium is located within a 1,000-m radius, and essentially all of the barium (calculated as 111 percent) is located within 1,250 m.

Boothe and Presley (1985) conducted a survey of sediment chemistries around six platforms in the Gulf of Mexico. They concluded that only a small fraction of the total barium discharged is present in sediments near the discharge site. They estimated only 1 - 1.5% of discharged barium within 500 m of the discharge at shallower sites (13 - 34 m) and only 9 - 12% at deeper sites (76 - 102 m). Similarly, within a 3 km radius, their estimates accounted for 5 - 7% at the shallower sites and 47 - 84% at the deeper sites. Statistically significant barium enrichment ($\geq$ twice background) existed in surface sediments at 25 of the 30 control stations located at a distance of 3 km from the drill sites. In the Santa Maria Basin, offshore Southern California, barium was found to be the only metal enriched in sediments near development drilling operations (Steinhauer et al., 1994).

Location		Zn							
Gulf of Mexico, Mustang Island Area [b]	ND	±(3-9X)	+(8-31X)	+(7-10X)	ND		−	−	+(6-25X)	+(2.5-3.5X)
Gulf of Mexico, Mustang Island Area			−	−	ND		−	−	−	ND
									+	
										+(4X)
										+(11.7X)
Trace Metal										+(1.2-1.4X)

[a]

suspended sediment

surficial sediment

Sporadic elevations in sediment trace metals also were noted by Boothe and Presley. Mercury and lead were significantly correlated to barium at several sites; distance dependent decreases were noted at two sites for mercury and one site for lead. Significant increases were noted generally only out to 125 m from the site; however the trend indicated increases perhaps to 300 - 500 m. The large statistical variability of the trace metal data set make statistical inferences difficult.

The general conclusion of this study is that barium and probably other drilling fluid contaminants associated with the settleable fraction of drilling muds appear to be relatively mobile. Thus, drilling discharges are expected to be spread over a large area (i.e., > 3 km from their discharge source) on time scales of a year or so. These data are consistent with other data that indicate drilling discharges can be distributed widely (Continental Shelf Associates, 1983; Ng and Patterson, 1982; Bothner et al., 1983 as cited in Boothe and Presley, 1985).

4.2   Discharge Modeling - Drilling Fluids

Two approaches have been used to project plume behavior for the purposes of water quality assessments. One approach uses a range of generalized operational, effluent, and ambient data to broadly assess plume behavior and water quality impacts. The second approach uses project-specific operational and a range of effluent and ambient data to assess these same parameters. Both approaches are discussed below; results of the water quality impact assessments are presented in Chapter 9 of this document.

The first approach uses two sets of Offshore Operator's Committee (OOC) Mud Discharge Model runs previously conducted for EPA Region 10 using a broad set of environmental and operational conditions. One set of OOC model scenarios (U.S. EPA Region 10, 1984) are based on a varied set of operational and environmental conditions for operations in Alaskan waters. A second set of model runs, intended to confirm and extend the earlier model runs conducted for Region 10, was completed for Region 10 by Dr. Maynard Brandsma (Brandsma Engineering, 1991). This last set of model runs was completed using the OOC Mud and Produced Water Discharge Model, Version 1.2F, which is an updated version of the 1983 OOC Mud Discharge Model used previously. Although these model runs were conducted for Region 10, many of these discharge scenarios are also generally appropriate to the present Gulf of Mexico analysis and were used to evaluate drilling fluids plume behavior.

The characteristics and results of these modeling exercises have been compiled and reviewed. A subset of cases was identified that comprise cases conducted for minimum water depths of 10 meters and at the maximum discharge rate authorized in the Gulf of Mexico permit (1,000 bbl/hr). This subset is believed to represent a reasonable range of potential drilling fluid discharge scenarios and, therefore, presents a reasonable indication of the dilutions and dispersions that may be expected for high rate drilling fluid discharges. Mean drilling fluids dilution among these 1,000 bbl/hr discharge scenarios, for 15-meter, 40-meter, and 70-meter water depth scenarios, were used by the Region for the purpose of conducting water quality assessments.

4.2.1 *OOC Mud Discharge Model*

The OOC Mud Discharge Model is the most general of the available drilling fluid plume models and is the discharge model used for both approaches. It uses LaGrangian calculations to track material (clouds) settling out of a fixed pipe and a Gaussian formulation to sum the components from the clouds. The OOC model includes the initial jet phase, the dynamic collapse phase, and the passive diffusion phase of plume behavior.

The minimum waste stream data input requirements for the OOC Mud Discharge Model include effluent bulk density and particle size distribution. The dispersion of up to 12 drilling fluid particle size solid fractions (i.e., settling velocity fractions) can be followed. For each constituent particle fraction, its settling velocity and its fractional proportion of total solids must be input to the model. The OOC model requires the following operational data input: the depth of the discharge, diameter of the discharge pipe, discharge rate, and orientation of the discharge relative to ambient currents. Ambient environmental data input requirements of the OOC model include current, density stratification, and bathymetry.

Operational data are generally adequate to fulfill the data input needs for the OOC Mud Discharge Model. Waste stream input data requirements are adequately addressed by existing information, with the possible exception of settling velocities for drilling fluid solids fractions. Currently, these data are both extremely limited and a key model parameter. Existing settling velocity data are available for only a very few drilling muds. Thus, lacking data on more mud samples, it is difficult to know if the available data adequately represent drilling fluids. Also, settling velocity profiles are a key parameter in the model, forming the basis for calculating the effect of gravitational setting of drilling fluid solids. Thus, any shift in the particle size distribution (i.e., settling velocity distribution) will have significant effects on the calculated behavior of the plume. Particle size (settling velocity) data should be considered minimally adequate.

4.2.2 *Derivation of Generalized Dispersion/Dilution Estimates*

The first set of model scenarios run for Region 10 was conducted over a range of environmental and operational conditions. The mud weight used, with the exception of one 9.0 lb/gal case, was a 17.4 lb/gal mud with a total suspended solids concentration (TSS) of 1,441,000 mg/l. Surface current speeds ranged from 2 cm/sec to 32 cm/sec; density stratification ranged from 0.008 σ_t/m to 0.1 σ_t/m. Operationally, discharge rates ranged from 100 bbl/hr to 1,000 bbl/hr, the discharge was located 1 foot below the water line, and the discharge pipe was 12 inches in diameter. Water depths ranged from 5 meters to 120 meters.

The second data set on modeling of drilling fluids dispersion and dilution (Brandsma Engineering, 1991) was conducted to confirm and extend the first data set prepared for Region 10. Thus, the input data used were the same as for the first data set. The principle alteration for this set of modeling data was that a newer, revised version of the OOC model was used. Also, in comparing the results of the earlier versus the more recent model runs, Brandsma noted that a computational error occurred in the derivation of soluble tracer dilution in the earlier data set. This error has been corrected for the first Region 10 data set in the ODCE review of the data.

4.2.3 *Model Results from Generalized Input*

The results of these two drilling fluids modeling data sets are compiled and presented in Table 4-3. Results have been sorted first by discharge rate and second, by dilution at 100 meters. These data have been analyzed in several ways. Data that were considered special cases of the model scenarios were eliminated from these analyses. These included model runs that excluded the rig wake effect from the model algorithm

Table 4-3. Summary of OOC Mud Model Drilling Fluid Plume Behavior

Case #	Water Depth (m)	Rate (bbl/h)	Current (cm/s)	Density Gradient (sigma-t/m)	100 m Dispersion	100 m Dilution
TT 8	10	100	10	0.07	3,859	2,579
TT 4	40	100	10	0.10	5,246	4,728
MB 3	5	250	10	0.10	2,318	222
MB 4	5	250	30	0.10	1,582	468
TT 18	5	250	10	0.02	6,109	662
TT 19	15	250	2	0.07	8,873	1,426
TT 20	15	250	10	0.07	2,558	1,617
MB 5	5	500	10	0.10	1,136	124
MB 6	5	500	30	0.10	770	211
MB 7	20	500	10	0.10	1,640	1,035
MB 8	20	500	30	0.10	1,626	1,583
MB 10	20	750	30	0.10	1,024	676
MB 9	20	750	10	0.10	1,305	789
TT 9	10	1,000	10	0.07	299	107
TT 5	5	1,000	10	0.02	4,810	127
TT 11	15	1,000	10	0.07	1,748	335
TT 6	10	1,000	10	0.07	1,785	341
TT 12	15	1,000	30	0.07	752	575
MB 11	20	1,000	10	0.10	942	655
TT 13	20	1,000	10	0.05	1,092	689
TT 14	40	1,000	10	0.01	731	755
TT 10	15	1,000	2	0.07	11,407	776
TT 3	40	1,000	10	0.10	905	818
MB 12	20	1,000	30	0.10	1,130	973
TT 15	70	1,000	10	0.04	1,803	1,721

Source: MB - Brandsma, 1991; TT - TetraTech, 1984.

and model runs that were conducted for pre-diluted drilling fluid discharges. Table 4-4 presents a summary of dilution results for data sorted by discharge rate. Table 4-5 presents a summary of dilution results for 1,000 bbl/hr discharges, sorted by water depth. These results are generally consistent with what would be expected for these discharges. Dilutions decrease with increasing discharge rates when they are considered in terms of their mean behavior, although there is considerable overlap between the ranges of dilution observed among the various discharge rates.

Table 4-4. Summary of OOC Mud Discharge Model Results by Discharge Rate

Discharge Rate (bbl/hr)	100-m Dilution Mean (Range)	100-m Dispersion Mean (Range
100	3,654 (2,579 - 4,728)	4,552 (3,859 - 5,246)
250	879 (222 - 1,617)	4,288 (1,582 - 8,873)
500	738 (124 - 1,583)	1,293 (770 - 1,640
750	733 (676 - 789)	1,165 (1,024 - 1,305)
1,000	656 (107 - 1,721)	2,284 (299 - 11,407)

Table 4-5. Summary of OOC Mud Discharge Model Results by Water Depth for High Weight (17.4 lb/gal) Muds Discharged at 1,000 bbl/hr

Water Depth (bbl/hr)	100-m Dilution Mean (Range)	100-m Dispersion Mean (Range)
5	127 (127)	4,810 (4,810)
10	224 (107 - 341)	1,042 (299 - 1,785)
15	562 (335 - 776)	4,636 (752 - 11,407)[a]
20	772 (655 - 973)	1,055 (942 - 1,130)
40	787 (755 - 818)	818 (731 - 905)
70	1,721 (1,721)	1,803 (1,803)

[a]   Includes the only model run for 17.4 lb/gal muds at 1,000 bbl/hr at 2 cm/sec current speed (all others run at 10-30 cm/sec); if deleted from data set, the mean dispersion at 15 m is 1,250-fold.

Likewise, the general trend for dilution is to increase water depth; the effect of water depth on dispersion appears less clear from this data set, with no well-defined trend. Others (U.S. EPA, Region 10, 1984) noted an apparent biphasic behavior in their more homogenous data set.

For the water quality assessment (see Chapter 9), the results of mean dilution at the maximum authorized discharge rate were used. For this assessment, mean dilution at 100 meters for a water depth of 15 meters was 562 dilutions; for water depths of 40 meters and 70 meters, the respective means were 787 dilutions and 1,721 dilutions.

4.3   Synthetic-Based Drilling Fluids

4.3.1 Dispersal and Accumulation of SBF Drill Cuttings

Laboratory dispersal experiments showed that the various types of SBF's displayed a relative dispersibility as follows: Ester > Di-Ether >> Linear alkyl benzene > PAO > Low-Toxicity Mineral Oil. It is expected that the IOs and LAOs, the most commonly used synthetics today, should fall between esters and PAOs in dispersibility.

Because most SBF cuttings do not disperse efficiently in the water column following discharge, the rapid settling results in accumulation on the bottom near the platform discharge site. The field studies reviewed (Neff et al., 2000) show a high degree of variability in the depth of the SBF cuttings piles and distribution of cuttings on the seafloor. The variety of methods used in the studies and variation in discharge depths, discharge rates, total volumes discharged and oceanic conditions prevent drawing clear relationships between cuttings pile depths and distributions and SBF type, water depths and cuttings mass.

Generally, the distance from the rig to the highest concentration of SBF cuttings on the bottom varies depending on distance from the discharge to the seafloor, the net water current speed, and cuttings density. Results of some field studies indicate that SBF cuttings are distributed very heterogeneously in surface and subsurface sediments around deep-water drilling sites. The uneven distribution of cuttings on the bottom appears to be caused by clumping of the hydrophobic SBF-coated cuttings falling to the seafloor in large clumps. The distributions of SBF cuttings accumulations on the bottom is controlled by the direction and velocity of water currents at different depths in the water column.

Because of the variability in the data reviewed, it is not possible to draw any firm conclusions about rates of biodegradation, dilution, or washout of different types of SBF cuttings from sediments. Generally, the rate of loss of SBFs, other than esters, from sediments appears to be low. Ester concentrations in sediments near rigs using ester SBFs were lower than concentrations of other SBFs near the platforms using other SBFs. This observation lends support to the hypothesis that esters biodegrade rapidly in sediments.

Based on the data reviewed, no clear relationship can be determined between concentrations of SBFs in sediments and water depth, mass of cuttings discharged, or mass of SBFs discharged. There was a trend for SBF cuttings concentrations in sediments near discharging platforms to decrease as water depth increased. In most cases, SBF cuttings do not penetrate and mix deeply into surface sediments near the platform. SBF concentrations usually are higher in the surface layer (0 - 2 cm) of sediments than in deeper layers (2 - 5 cm and 5 - 8 cm). Approximately a year after completion of drilling, concentrations of SBF in the surface layer of sediments often decrease; however, concentrations at greater depths in the sediment core may increase or decrease. Temporal changes in SBF concentrations below the sediment

surface probably are controlled by the amount of sediment reworking (by bioturbation and current-induced bed transport) and biodegradation. After more than a year, SBF concentrations at all depths in sediment may decline to low values, particularly if ester SBF cuttings were discharged.

The distribution of SBF concentrations in sediments around platforms discharging SBF cuttings varied widely from one site to another. The distribution of SBF cuttings piles around drilling rigs in the UK Sector of the North Sea ranges from less than 2800 m^2 to 94,250 m^2 . The cuttings are not evenly distributed in sediments around the rig with most cuttings settling in the direction of the net current flow.

The distance from the rig to the highest concentration of SBF cuttings on the bottom varied depending on distance from the discharge to the seafloor, the net water current speed, and cuttings density. In studies of SBF discharges to the UK Sector of the North Sea the highest concentrations of SBF in sediments were located 0 m to 224 m from the rig immediately after drilling. Approximately one year after completion of drilling, the highest SBF concentrations in sediments were located 5 m to 153 m from the former drilling sites. The distance from the rig sites to sediment SBF concentrations below about 1,000 mg/kg ranged from 40 m to about 500 m from the rigs.

4.3.2 Biodegradation of SBFs

Microbial metabolism is the main mechanism of degradation of SBF base materials into harmless byproducts. Natural populations of sediment-dwelling bacteria, fungi, and protists are able to biodegrade some hydrocarbons and related oxygen-containing organic chemicals (e.g., esters, ethers, acetals) and use the carbon fragments as a source of nutrition.

Hydrocarbons vary in their susceptibility to biodegradation. The biodegradation of paraffins and olefins decreases sharply with increasing carbon chain length and molecular weight. As a result, high molecular weight, insoluble SBF base chemicals, such as PAOs, are less bioavailable and biodegradable than lower molecular weight, slightly soluble base chemicals, such as IOs. As a general rule, linear hydrocarbons are more easily biodegraded than branched or aromatic hydrocarbons. Biodegradation rate of linear paraffins decreases as chain length increases. Branching of hydrocarbon chains tends to slow biodegradation. Carbon-carbon double bonds and internal oxygen atoms (e.g., esters) are more readily attacked by microbes than carbon-carbon single bonds. Hydrocarbons are biodegraded mainly by oxidation; therefore, biodegradation of SBF base materials and other hydrocarbons is much more rapid under aerobic conditions than in anaerobic environments.

A normal alkane (e.g., linear paraffin) or an alkene (e.g., LAO, IO, and PAO) is oxidized by microbes to an alcohol; the alcohol is oxidized further to a fatty acid. Two atoms of oxygen are consumed for each atom of fatty acid formed. Fatty acids are storage and structural nutrients for all plants and animals. The fatty acids derived from oxidation of SBF base chemicals are oxidized two carbons at a time through oxidation. The resulting acetate (CH_3COOH) molecules are incorporated into the energy and synthetic pathways of the microorganism. Thus, SBF base chemicals are biodegraded completely under aerobic conditions, with the reduction of a large amount of oxygen. Aerobic biodegradation of SBFs may deplete the oxygen in sediments, rendering the sediments anaerobic, if loading of the sediments with biodegradable organic matter from SBF cuttings is high and aeration of sediments is slow. In the absence of oxygen, SBF base chemicals are dehydrogenated to alcohols that are converted to

fatty acids via chemical reactions are very inefficient under anaerobic conditions, and their rate probably limits the overall net rate of SBF biodegradation in marine sediments. Carbon-carbon double bonds and ester linkages are more easily oxidized than carbon-carbon single bonds by marine anaerobic bacteria. Thus, esters and unsaturated SBF base chemicals would be expected to biodegrade more rapidly than paraffins, linear alkyl benzenes, ethers, and acetals in anoxic sediments. Under anaerobic conditions, fatty acid oxidation also is inefficient. Alternatives to oxygen (e.g., NO_3^-, SO_4^{-2}, and CO_2) are used by the microbes to oxidize fatty acids, producing byproducts, such as hydrogen sulfide, ammonia, and methane, that are toxic to some sediment-dwelling marine organisms. Sulfate is abundant in seawater (~ 29 mM) and marine sediments; therefore, it is the dominant terminal electron acceptor for microbial oxidation of SBF base chemicals in anoxic marine sediments. Methanogenesis (reduction of CO_2 to CH_4) occurs only when most of the available sulfur has been reduced to sulfide. Sulfate reducing bacteria are more aggressive than methanogens, and olefins and esters should biodegrade more rapidly in marine sediments than indicated by anaerobic biodegradation tests, most of which are based on methanogenesis. The most important environmental factors affecting biodegradation rate of SBFs in sediments are temperature, oxygen concentration, and seafloor energy.

Results of laboratory biodegradation tests reviewed by Neff et al. (2000) indicate that aerobic and anaerobic biodegradation rates of synthetics occur in the following order: ester>LA   IO>PAO> acetal>ether. Mineral oils are less biodegradable than SBF base chemicals, particularly under anaerobic conditions.

Considering the high concentrations of SBFs measured in surficial sediments within 100 m of some offshore platforms discharging SBF cuttings, it is probable that most SBF biodegradation will occur under anaerobic conditions after sediment oxygen concentration is reduced to low levels by the initial aerobic biodegradation of the SBF cuttings. In low energy environments where cuttings dispersion at the seafloor is a minor factor, anaerobic degradation of SBF cuttings probably is the rate-limiting step in recovery of benthic marine ecosystems contaminated with SBF cuttings. Anaerobic biodegradation rate is highest for esters, followed by LAOs. In general, SBF base chemicals, other than ester, do not biodegrade anaerobically at a substantially higher rate than mineral oils used in OBFs. Alkylbenzenes are not biodegraded under anaerobic conditions. Of the possible degradation products, alcohols are highly biodegradable, and ethers are resistant to anaerobic biodegradation.

4.4 Produced Water

The major processes affecting the fate of discharged produced water and associated chemicals include dilution and advection, volatilization, and adsorption/sedimentation. Hydrocarbons that become associated with sedimentary particles by adsorption can accumulate around production platforms, either settling to the seafloor through the water column or more directly through bottom impact of the discharge plume. Sediment contamination by produced water hydrocarbons was observed in shallow water studies at Trinity Bay, Texas (Armstrong et al., 1979) and at coastal Texas and Louisiana sites (Roach et al., 1992; Boesch and Rabalais, 1989; Rabalais et al., 1992). Roach et al. (1992) sampled sediments in the vicinity of produced water

discharges at two coastal sites in Texas. Elevated levels of PAHs, aliphatics, and oil and grease were observed to a distance of 370 m from the discharge. Boesch and Rabalais (1989) noted that concentrations of naphthalenes in the sediment were enriched compared to effluent levels (21 mg/kg in the sediment versus 1.62 mg/liter in the effluent) and naphthalene levels were elevated in the immediate vicinity of the discharge with a subsurface concentration maximum in the sediment. Rabalais et al. (1992) compared sediment contamination and benthic community effects at 14 study sites in Louisiana (Table 4-6). Alkylated PAH were found to the maximum distance of the study transects at two sites (to 1,000 and 1,300 m) and from <100 to 500 m at the other sites. The two sites with no contaminants detected had outfalls that directed flow to a holding pond or marsh area. Benthic community effects were detected to a maximum distance of 800 m.

The sediment accumulation observed in these shallow water studies is provided for comparison and is not expected to directly compare to the open Gulf areas covered by the general permit for the eastern Gulf. Studies of sediment impacts for open waters are not available to the extent that coastal studies are. One study, Neff et al. (1988), reports little chemical contamination at their offshore study sites that exceeded a 300 m radius. Neff (1997) recently reviewed the available scientific literature on the fates and effects of produced water in the ocean. Saline produced waters dilute rapidly upon discharge to well-mixed marine waters. Dispersion modeling studies of the fate of produced water differ in specific details but all predict a rapid initial dilution of discharges by 30- to 100-fold within the first few tens of meters of the outfall, followed by a slower rate of dilution at greater distances (Smith, 1993; Terrens and Tait, 1993; Smith et al., 1994; Stromgren et al., 1995; Brandsma and Smith 1996). Terrens and Tait (1993) modeled the fate of produced water discharged to the Bass Strait off southeastern Australia. Under typical oceanographic conditions for the area, the produced water is diluted nearly 30-fold within 10 m of the discharge and by 1,800-fold 1,000 m down-current of the produced water discharges.

Table 4-6. Comparison of Extent of Sediment Contamination, and Benthic Community Impacts for Produced Water Discharges in the Gulf of Mexico

	Discharge (bbl/day)	Receiving Water Depth (m)	Environment	Zone of Sediment Contaminants (m)	Extent of Benthic Community Impacts (m)
1,2	48,000	4-5	Dredged Bayou	1,300	
1,2	26,000	3-4	Canals Near Bay	1,000	700
1,2	21,000	1.5-2	Miss. R. Distributary	360	800
1,2	20,200	2	Marsh, Dredged Canal	250	100
3	4,000-10,000	2	Marsh, Dredged Canal	450	300
1,2	3,700	3	Marsh, Miss. R. Distributary	None	None
4	3,700	3	Open Bay (near pass)	250-300	None
4	3,700	2	Open Bay	None	150
5	3,700	2	Dredged Canal	100	None
5	2,800	12	Shallow Shelf, Bayou	500	20
6	2,500	2-3	Dredged Canal	100	250
	120-2,000	2-3	Dredged Canal	500	100
		20	Shallow Shelf	200	NA

References:

Source: Rabalais et al., 1992.

Brandsma and Smith (1996) modeled the fate of produced water discharged under typical Gulf of Mexico conditions. For a median produced water discharge rate of 115 m^3/d (772 bbl/d), a 500-fold dilution was predicted at 10 m from the outfall and a 1,000-fold dilutions was predicted at 100 m from the outfall. For a maximum discharge rate of 3,978 m^3/d (25,000 bbl/d), a 50-fold dilution was predicted at 100 m from the outfall. High volume discharges of warm high-salinity produced water to the North Sea are diluted by about 500-fold within about 60 m of the outfall under well-mixed water column conditions. Under conditions of stratified water column, a 300-fold dilution is reached 60 m from the discharge (Stephenson et al., 1994). Further dilution is slower; a 1,000-fold dilution is attained after about 1 hour when the produced water plume has drifted about 1,000 m.

Field measurements of produced water dilution are highly variable, but confirm the predicitons of modeling studies that dilution is rapid. Continental Shelf Associates (1993) reported that radium from a 6,570 bbl/d produced water discharge in a water depth of 18 meters in the Gulf of Mexico was diluted by a factor of 426 at 5 m from the discharge, and by a factor of 1,065 at 50 m from the discharge. Smith et al. (1994) used a dye tracer to measure dilution of produced water being discharged at a rate of 2,900 bbl/d to 6,500 bbl/d in a water depth of 82 m and found a 100-fold dilution within 10 m of the discharge and a 1,000-fold dilution within 103 m of the discharge. Somerville et al. (1987) measured a 2,800-fold dilution of produced water 1,000 m downcurrent from a North Sea produced water discharge. Rabalais et al. (1992) were able to measure elevated (compared to background) concentrations of radium, but not volatile hydrocarbons, to about 1,000 m downcurrent of a high-volume produced water discharge to shallow coastal waters of Louisiana.

Chemical processes important to the fate of produced water constituents generally are those that affect metal and petroleum hydrocarbon behavior in marine systems. Factors affecting metals have been described above under drilling fluids. An important factor affecting the fate of hydrocarbons in produced water is volatilization. Produced water contains a high fraction of volatile compounds (e.g., benzene), which can be lost from the system over time. However, because produced water can be much more dense than seawater (salinities >150 ppt are not uncommon), discharge plumes sink rapidly. Thus, elevated levels of benzene in bottom water have been observed in shallow coastal waters (Boesch and Rabalais, 1989; Rabalais et al., 1992).

For compounds with higher molecular weights, a major chemical process involves biodegradation of compounds. Polynuclear aromatic hydrocarbons tend to be more resistant to such degradation and, thus, can persist in the environment (primarily in sediment) for extended periods. The subsequent fate of petroleum hydrocarbons associated with sediments will depend on resuspending and transporting processes, desorption processes, and biological processes. Because produced waters provide a continuous input of light aromatic hydrocarbons over the life of a field (generally 10 to 30+ years), there is the potential for these chemicals to accumulate in sediments. This differs from oil spill situations wherein the chemicals are rapidly lost and the sediments generally exhibit a decline of lighter aromatics with time.

The most abundant hydrocarbons of environmental concern in produced water are the light, one-ring aromatic hydrocarbons. Because they are volatile, they can be expected to evaporate rapidly from the water following produced water discharge. Brooks et al. (1980) reported that the maximum concentration of benzene measured in seawater immediately below the produced water discharge pipe at

a production platform in the Buccaneer Field off Galveston, Texas was 0.065 ug/l, representing a nearly 150,000-fold dilution compared to the concentration of benzene in the produced water effluent (9,500 ug/l). Concentrations of total gaseous and volatile hydrocarbons, including BTEX aromatics (75 percent of the total) decreased from 22,000 ug/l in the effluent, to 65 ug/l at the air:water interface below the outfall, to less than 2 ug/l in the surface water about 50 m away, indicating very rapid evaporation and dilution of the volatile components of the produced water. Concentrations of volatile liquid hydrocarbons discharged with produced water (600 bbl/d) at the Buccaneer Field were reduced on the order of 10^{-4} to 10^{-5} within 50 m from the platform (Middleditch, 1981).

BTEX concentrations in the upper water column near production platforms off Louisiana ranged from 0.008 to 0.332 ug/l (Sauer, 1980) compared to background concentrations of 0.009 to 0.10 ug/l of benzene in surface waters of the outer continental shelf off Texas and Louisiana (Sauer et al., 1978). These compounds are very volatile with half-lives in the water column of a few hours or days, depending on water temperature and mixing conditions.

Terrens and Tate (1996) measured concentrations of BTEX and several PAHs in ambient sea water 20 m from an 11 million liter/d (69,000 bbl) produced water discharge from a platform in the Bass Straits off Australia. There was an inverse relationship between molecular weight (and thus, volatility) and the dilution of individual aromatic hydrocarbons. Individual monoaromatic hydrocarbons were diluted by 53,000-fold (benzene) to 12,000-fold (xylenes). PAHs were diluted by 12,000-fold (naphthalene) to 2,000-fold (pyrene). Concentrations of higher molecular weight PAHs were below the detection limit (0.0002 ug/l) in the ambient sea water 20 m from the outfall. The inverse relationship between molecular weight of the aromatic hydrocarbons and their rates of dilution probably was attributed to the high temperature (95° C) of the discharged produced water.

Dilution of BTEX from produced water is less rapid where a large volume of highly saline produced water is discharged to poorly mixed, low-salinity estuarine waters. The concentration of total volatile hydrocarbons (including BTEX) approached 100 ug/l on one occasion in the bottom water in the vicinity of three produced water discharges (total volume ~ 43,000 bbl/d) to Pass Fourchon, a shallow marsh area in south Louisiana (Rabalais et al., 1991). BTEX compounds do not adsorb strongly to suspended or deposited marine sediments. Their concentrations in sediments near produced water discharges are usually low (Armstrong et al., 1979; Neff et al., 1989).

However, higher molecular weight aromatic and aliphatic hydrocarbons may accumulate in sediments near produced water discharges (Armstrong et al., 1979; Neff et al., 1989; Means et al., 1990; Rabalais et al., 1991). In well-mixed estuarine and offshore waters, elevated concentrations of saturated hydrocarbons and PAHs in surficial sediments may be observed out to a few hundred meters from a large-volume produced water discharge. In shallow, poorly mixed estuarine environments, elevated concentrations of PAHs in sediments may be detected to distances of at least 1,300 m from large-volume produced water discharges (Rabalais et al., 1991; 1992). Sediment contamination is greatest and extends the farthest from the discharge sites where large volumes of produced water (48,000 to 145,000 bbl/d) have been discharged to shallow (2 to 5 m) salt marsh canals.

4.4.1 Biological Transport Processes

Biological transport processes occur when an organism performs an activity with one or more of the following results.

- An element or compound is removed from the water column
- A soluble element or compound is relocated within the water column
- An insoluble form of an element or compound is made available to the water column
- An insoluble form of an element or compound is relocated.

Biological transport processes include bioaccumulation in soft and hard tissues, biomagnification, ingestion and excretion in fecal pellets, and reworking of sediment to move material to deeper layers (bioturbation).

Ingestion and Excretion

Organisms remove material from suspension through ingestion of suspended particular matter and excretion of this material in fecal pellets. These larger pellets exhibit different transport characteristics than the original smaller particles. Houghton et al. (1981) notes that filter-feeding plankton and other organisms ingest fine suspended solids (1 µm to 50 µm) and excrete large fecal pellets (30 µm to 3,000 µm) with a settling velocity typical of coarse silt or fine sand grains. The study also notes that copepods are important in forming aggregate particles.

Zooplankton have been found to play a major role in transporting metals and petroleum hydrocarbons from the upper water levels to the sea bottom (Hall et al., 1978). The largest fraction of ingested metals moves through the animal with the unassimilated food and passes out with the fecal pellets in a more concentrated state (Fowler, 1982). Zooplankton fecal pellets have also been found to contain high concentrations of petroleum oil, especially those of barnacle larvae and copepods. Hall et al. (1978) calculate that a population of calanoid copepods grazing on an oil slick could transport three tons of oil per square kilometer per day to the bottom.

Bioaccumulation and Biomagnification

Studies assessing biomagnification of certain petroleum hydrocarbons are more limited than for other pollutants. The data available suggest that these contaminants are not subject to biomagnification. One reason for this observation is that the primary source of these compounds for organisms may be absorption from the water column rather than ingestion. Additionally, biological half-times of some petroleum hydrocarbons may be short, with many species purging themselves within a few days.

There is some evidence that hydrocarbons discharged with produced water are bioaccumulated by various marine organisms. In a central Gulf of Mexico study (Nulton et al., 1981), analyses revealed the presence of low levels of alkylated benzenes, naphthalenes, alkylated naphthalenes, phenanthrene, alkylated three-ring aromatics, and pyrene in a variety of fish and epifauna. Isomer distributions of alkylated benzenes and naphthalenes were similar to those seen in crude oil.

Middleditch (1980) analyzed hydrocarbons in tissues of organisms in the Buccaneer Field. During the first two years of the study, tissue from barnacles from the platform fouling community at depths approximately 3 m below the surface contained up to 4 ppm petroleum alkanes. Middleditch (1980), in studying the fouling community and associated pelagic fish, found that many species were contaminated with hydrocarbons discharged in produced water. Middleditch claims that biodegradation of petroleum hydrocarbons in the barnacles was apparently efficient. Analyses of the fouling mat on the platform revealed that most samples contained petroleum hydrocarbons, and concentrations were particularly high in those collected just below the air/sea surface.

Middleditch (1980) found petroleum hydrocarbons in 15 of 31 fish species examined around the Buccaneer Field platform. Analyses were focused on four species--crested blenny, sheepshead, spadefish, and red snapper. Virtually every specimen of crested blenny examined contained petroleum alkanes. In this species, the n-octadecane/phytane ratio was similar to that of produced water but the n-octadecane/pristane ratio is distorted by the presence of endogenous pristane of biogenic origin. The mean alkane concentration in this species was 6.8 ppm. This species feeds on the platform fouling community, and it was suggested that this food was the source of petroleum hydrocarbons to the fish. Similar results were obtained with sheepshead, which also partially feed on the platform community. Petroleum alkanes were found in about half of the muscle samples and in about one quarter of the liver samples. The mean alkane concentration in these tissues were 4.6 and 6.1 ppm, respectively. Spadefish exhibited lower concentrations of alkanes in muscle and liver (0.6 and 2.0 ppm), and this species does not utilize the platform fouling community as a food source to the same extent as the two previously described species. Lower levels of alkanes were also observed in red snapper (1.3 ppm in muscle, and 1.1 ppm in livers).

With one exception, most shrimp analyzed by Middleditch did not contain alkanes. This probably reflects the highly migratory behavior of these animals. Similarly, the petroleum hydrocarbons were not found in white squid. Middleditch also examined nine benthic organisms for petroleum hydrocarbons. Yellow corals (*Alcyonarians*) contained alkanes, but Middleditch suggested these could be of biogenic origin. Various hydrocarbon profiles were observed in species. Few of the specimens of winged oyster (*Pteria colymbus*) contained petroleum alkanes while they did contain methylnaphthalenes and benzo(a)pyrene. The results presented above, however, are rendered ambiguous inasmuch as Middleditch may not have clearly differentiated between biogenic and petrogenic alkanes.

4.4.2 Discharge Modeling - Produced Water

The fate of produced water discharges was projected using the CORMIX expert system, which was developed as a regulatory assessment tool for the EPA Environmental Research Laboratory at Athens, Georgia (Doneker and Jirka, 1990). A review of the model by LimnoTech Inc. (1993) for application to the OCS Federal waters resulted in the modified version used for the projections in this assessment.

4.4.2.1   CORMIX Expert System Description

The Cornell Mixing Zone Expert System (CORMIX) is a series of software subsystems for the analysis, prediction, and design of aqueous conventional or toxic pollutant discharges into watercourses (Doneker and Jirka, 1993). CORMIX (Version 2.10) was developed to predict the dilution and trajectory

of submerged, single port discharges of arbitrary buoyancy (positive, negative, neutral) into water body conditions representative of rivers, lakes, reservoirs, estuaries, or coastal waters (i.e., shallow or deep, stagnant or flowing, uniform density or stratified). CORMIX assumes steady state flow conditions both for the discharge and the ambient environment.

The CORMIX expert system emphasizes the geometry and initial mixing of the discharge, predicting concentrations and dilutions, and the shape of the regulatory mixing zone. CORMIX requests necessary data input, checks the input data for consistency, assembles and executes the appropriate hydrodynamic models, interprets results of the simulation with respect to the specified legal mixing zone requirements (including toxic discharge criteria), and suggests design alternatives to improve dilution characteristics.

CORMIX uses the expert system shell VP-Expert (Paperback Software, Inc.) and FORTRAN. CORMIX uses knowledge and inference rules, based on hydrodynamic expertise captured in the system, to classify and predict jet mixing. CORMIX was developed with the intent to provide an expert system that would work for a large majority of typical discharges (better than 95%), ranging from simple cases to fairly complex cases.

CORMIX requires input of water depth, selection of stratification profile (it provides four profiles from which to choose), surface/bottom water densities and stratification height if one exists, ambient current velocity (uniform), distance to the nearest bank, outfall port diameter, flow rate, depth of the outfall port (restricted to the lower third of the water column), vertical and horizontal discharge angles, effluent density, and the shape and dimension of regulatory mixing zones.

In response to industry comments on a proposed general NPDES permit issued by EPA Region 6, EPA requested a review of CORMIX to determine the system's applicability to discharges to open waters of the Gulf of Mexico. While it was determined that CORMIX was the best choice of the dispersion/ dilution models available, it was also determined that two adjustments were needed to make the far-field projections more accurate.

The first adjustment concerns the limitation imposed by the system requiring that the discharge pipe opening be located in the bottom one-third of the water column. For produced water outfalls located at or above the water surface and is a negatively buoyant effluent (such as produced water), this configuration does not provide an accurate prediction of scenarios where the full water column is available for mixing. To correct for this, the water column and discharge densities have been inverted for two of the three discharge modeling scenarios where surface discharges occur, in the following manner. (The remaining case, where the discharge is shunted into the lower third of the water column, no adjustments to CORMIX were necessary.)

Based on a linear stratification with a density gradient (σ_t/m) of 0.163 kg/m^3/m, the bottom density is calculated using a surface density of 1,023 kg/m^3. The water column is "inverted" by using the surface density as the bottom density and calculating a new surface density, keeping the density differential constant (e.g., for a 10 meter water depth, the new surface density would be 1,023 kg/m^3- (10 * 0.163 kg/m^3) = 1,021.37 kg/m^3). The effluent density is inverted to create a positively buoyant plume keeping the produced water:ambient density differential consistent with the original scenario. This is

accomplished by reducing the effluent density at the outfall by the difference between it and the original ambient density (e.g., the initial density differential of 1,070 kg/m³ - 1,023 kg/m³ = +47 kg/m³ is transformed into a density differential of -47 kg/m³ by changing the effluent density to 1,023 kg/m³ - 47 kg/m³ = 976 kg/m³). The inverted scenario is run through the CORMIX system with the discharge located at the seafloor creating a mirror image of a negatively buoyant discharge located just below the water surface. Trial runs of the CORMIX system verify that these scenarios produce identical results.

The second adjustment to the CORMIX system corrects for an underestimation of far-field dilutions as discussed in Wright (1993). For model projections that do not result in the plume impacting the seafloor (or the surface in the case of the inverted scenario), Brook's 4/3 power law is applied to the control volume outflow results of the model at the end of the impingement zone to predict the dilutions at the edge of the mixing zone. The derivation from the Brook's equation used to calculate farfield dilution is:

$$C_i = \mathrm{erf}[(1.5/((1 + 8\ A\ H^{4/3}\ (t/H^2))^3 - 1))^{1/2}]$$

where,

H	=	the width of the collapsed plume
A	=	0.000453 m²/³/s
t	=	travel time from the end of the plume collapse to 100 m (edge of the mixing zone) (100/u-T); where T is the time to complete the collapse phase
erf	=	the error function
C_i	=	the maximum concentration in the far field after travel time t_i.

The input needed for this equation is provided by the CORMIX output.

4.4.2.2 Derivation of Dilution Estimates

Input data for stratification conditions in the CORMIX model predictions used for the general assessment of produced water dilution were primarily based on a study by Temple et al. (1977). A study transect off Mobile Bay was monitored for temperature and salinity over one year. The 7- and 14-meter stations were used to determine the average surface water density and density gradient in the water column. For the existing produced water outfalls located offshore Alabama, a surface density of 1,023 kg/m^3 and a gradient (σ_t/m) of 0.163 kg/m^3/m were used. The effluent density of 1070 kg/m^3, used as input for the model, was derived from data obtained from the Louisiana Department of Environmental Quality (*Avanti* Corporation, 1992). The density represents a produced water with a salinity of 100 ppt (approximately the lower 33rd percentile of coastal and offshore Louisiana produced water chlorinity) and an effluent temperature of 105˚F (approximately the upper 90th percentile of coastal and offshore Louisiana produced water temperature).

The current speed used for this assessment of produced water dilution (5 cm/sec) is the median of current speeds recorded for offshore Alabama by Texas A&M (1991). The current meter was placed at a 10 meter depth in 30 meters of water.

Operational data for the three existing produced water outfalls were supplied by the operators at the request of Region 4. This data as well as other input parameters needed for the CORMIX model are listed in Table 4-7. Shell, operating in Mobile Block 821, is located in 49 feet (15.25 m) of water. The outfall is shunted to 40 feet (12.2 m) below the water surface and the average produced water discharge rate is 1500 bbl/day from a 35-inch pipe. Because the outfall is within the bottom one-third of the water column, inversion of the water column densities was not needed. Also, because CORMIX indicated plume interaction with the seafloor, the Brook's equation modification for the farfield dilution was not applied in this case. Chevron is operating in Mobile Block 990 located in 54 feet (17.5 m) of water with the outfall located above the surface of the receiving water. The discharge averages 450 bbl/day from a 4-inch pipe. Callon Petroleum is located in Mobile Block 908 in 66 feet (21.1 m) of water with the outfall located above the receiving water surface. The average discharge rate is 2 bbl/day from a 6-inch pipe.

4.4.3   Model Results

The results of the CORMIX model are presented in Table 4-7 for a 100-meter mixing zone. These results are used for the water quality analysis in Chapter 9 of this document. Both the Chevron and Callon Petroleum produced water outfalls are located above the water surface. In these cases the ambient water densities and effluent:ambient density differential were invertet; because the discharge plume does not impact the surface, the Brook's equation was used to estimate far-field dilution. The CORMIX dilution at 100 m, without the Brook's modification was used for the Shell facility produced water modeling scenario.

**Table 4-7. Summary of CORMIX Input Parameters and
Model Results for Produced Water Discharges**

Input Parameter[a]	Shell (MOB 821)	Chevron (MOB 990)	Callon Petroleum (MOB 908)
Water Depth	49 ft. (15.25 m)	54 ft. (17.46 m)	66 ft. (21.1 m)
Pipe Depth	40 ft. (12.2 m) or 3.05 m from bottom	Above surface or 0 m from bottom	Above surface or 0 m from bottom
Pipe Diameter	35 in. (0.889 m)	4 in.(0.1016 m)	6 in. (0.1524 m)
Discharge Rate (bbl/d)	1,500 bbl/day	450 bbl/day	2 bbl/day
Current Speed (m/s)	0.05 m/s	0.05 m/s	0.05 m/s
Ambient Surface Density (kg/m^3)	1,023	1,020.15	1,019.56
Ambient Bottom Density (kg/m^3)	1,025.49	1,023	1,023
Density Stratification (sigma-t/m)	0.163	0.163	0.163
Produced Water Density (kg/m^3)	1,070	976	976
Dilutions at 1,000 m	333	3,570	89,235

[a] Input data provided to Region 4 by operators; current speed and density stratification determined from data for the Gulf of Mexico offshore Alabama (Texas A&M, 1991; Temple et al., 1977).